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REVIEW

Recent Advances in the Science of Cannabis-Impaired Driving

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Abstract

Purpose of Review To examine cannabis-induced effects on driving performance. Prior systematic reviews consistently reveal that Δ^9-tetrahydrocannabinol (THC) impairs driving performance. The present narrative review summarized evidence on the acute and residual effects of cannabis on driving performance from controlled experimental research completed in the past five years. Expanding on prior research, recent studies examine individual and combined effects of THC and cannabidiol (CBD), combined effects of cannabis and alcohol, and a variety of cannabis administration modes.

Recent Findings Cannabis with THC acutely impairs driving without significant residual deficits. CBD does not acutely impair driving performance, although relatively low doses (< 300 mg) were used in most studies. The combination of alcohol and THC results in additive effects that amplifies impairment. In line with prior research findings, cannabis-induced driving impairment is consistently observed within the first hour after use and impairment remains detectable for ~4–5 h post-inhalation; studies testing oral and sublingual cannabis administrations were sparse. Participants were willing and ready to drive shortly after using cannabis while their driving skills were objectively impaired.

Summary Despite clear evidence of cannabis-induced driving impairment, a consistent impairment standard that can be used outside the laboratory is lacking. More research focused on sensitive biomarkers combined with technologically-advanced behavioral methods is needed to improve the precision and accuracy in determining cannabis-induced driving impairment. Future studies should focus on novel oral and oromucosal formulations emerging on the legal cannabis market.

Keywords Cannabis · Tetrahydrocannabinol · Driving · Impairment · Driving under the influence

Introduction

Driving Under the Influence of Cannabis (DUIC) is a growing public health concern, both in terms of prevalence and associated costs. Almost a third of individuals who use cannabis and 63.8% of those with symptoms suggestive of Cannabis Use Disorder report past year DUIC [1].Predicted probabilities of DUIC are highest for those who use more frequently, with over three quarters reporting using cannabis while driving [1, 2]. Cannabis-related traffic fatalities have significantly increased since cannabis legalization, particularly in the context of recreational cannabis legalization in the US and beyond [3]. Cannabis is now the most prevalent substance in the blood of seriously or fatally injured roadway users at 25.1%, followed by alcohol at 23.1% [4]. In contrast to stable alcohol fatality trends, cannabis-involved motor-vehicle crashes more than doubled from 2000 to 2018 [5]. Fatalities co-involving cannabis and alcohol have also doubled from 4.8% in 2000 to 10.3% in 2018 [5]. The increase in DUIC is attributed to several factors, including increased cannabis use prevalence, higher concentrations of THC in legal cannabis products, growing acceptance of cannabis and the perception that it is safe, and lack of universal DUIC standards and enforcement [3, 6–9]. The present review summarizes the literature on the effects of cannabis on driving performance, highlighting controlled studies completed in the past five years that specifically examined commonly used cannabinoids, combined effects of cannabis and alcohol, and duration of impairment following acute use.

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Driving-Related Impairment: Epidemiological Studies and Experimental Research on Cognitive Impairment

A review of five meta-analyses of case-control, culpability, and cohort studies [10–14] found that the risk of motor vehicle crashes, including fatal ones, is significantly increased and in some studies doubled after cannabis use [15]. Cannabis dose is classified based on the quantity of Δ^9-tetrahydrocannabinol (THC), the primary psychoactive component of the cannabis plant. Controlled experimental research demonstrated dose-dependent effects of cannabis on complex psychomotor functioning directly relevant to driving ability [16]. Dose-dependent effects of THC were found on all eight areas of executive functioning deemed critical to driving behavior by the International Council on Alcohol, Drugs, and Traffic Safety: attention and information processing, cognition and judgment, divided attention, motor performance and maneuvers, perception, risk-taking and impulsivity, sustained attention, and tracking and steering [17, 18]. An increased reaction time (RT; i.e., increased time to respond to stimuli) is also among the most common cannabis-associated impairments. A meta-analysis revealed significant THC-induced impairment on divided attention, tracking performance, information processing, conflict control, fluid intelligence, reaction time, fine motor functioning, sustained attention, and working memory [19]. This impairment was consistently less pronounced among people with regular cannabis use rather than those who used occasionally due to higher drug tolerance [20, 21].

Measures of Driving Performance

Experimentally-controlled studies have demonstrated dose-dependent effects of THC on impaired driving ability across a number of outcomes [22–26]. A meta-analysis of controlled trials found detrimental effects of THC in the small-to-medium magnitude range on Standard Deviation of the Lateral Position (SDLP; n = 15), lateral control (n = 16), and reaction time (n = 8) (Hedges' g = 0.25–0.47) but not on measures of car following headway/headway variability, speed, or speed variability [19]. This meta-analysis included trials in which driving performance was assessed within 1.5 h of THC being smoked, vaporized, administered intravenously or between 1.5 and 3.5 h of oral THC administration. Cannabis and cannabis-alcohol combinations also acutely increased collisions on a driving simulator [27, 28]. Variability in speed and increased headway have been acutely affected by THC in some individual studies [25, 29], but indices other than SDLP have not been as consistently validated against blood alcohol concentration (BAC) thresholds [24, 30].

SDLP, measured in centimeters, is an index of lateral position relative to lane-line delineation and is an objective measure of continuous driving behavior [31]. Other measures of lateral control include lane departures and minimum and maximum lateral acceleration. SDLP is considered the most sensitive, validated, and reliable driving impairment measure [19, 32], demonstrated to differentiate varying levels of THC and alcohol concentrations in blood [24, 30]. SDLP has been used as a primary evaluation outcome in studies assessing the influence of medications and drugs on driving performance [31–33]. Numerous experimental and on-road studies have consistently demonstrated its sensitivity to THC's acute effects and impairing effects of alcohol, with THC and alcohol dose-dependently increasing SDLP [24, 31].

As an experimental measure, SDLP has not been directly validated against crash risk, which is an epidemiological measure [30]. Instead, performance decrements on this measure have been calibrated to BAC, which in turn is highly correlated with crash risk [33]. The lowest criterion value defining drug-induced driving impairment established in alcohol calibration studies for the standard driving test is a Δ2.4 cm SDLP associated with a BAC of 0.5 mg/ml (i.e., ΔSDLP between BAC 0.05% and BAC 0%) [31]. Controlled cannabis administration studies have consistently demonstrated dose-dependent THC-induced ΔSDLP above the 2.4 cm threshold [19]. Furthermore, the average SDLP increase of 2.5 cm during highway driving at a BAC of 0.5 g/l supports the clinical relevance of this cutoff for driving impairment [34]. In placebo-controlled studies that directly compared driving impairment due to cannabis and due to alcohol, decrements in SDLP for cannabis were comparable or greater than those for alcohol (e.g., 8 cm increase for 38 mg THC vs. 5 cm 0.05% BAC [25, 30].

Driving Simulator vs. On-Road Controlled Studies

On-road studies have demonstrated THC dose-dependent impairments on SDLP and reaction time during actual driving in normal traffic conditions in individuals who use cannabis both occasionally and heavily [22, 29, 35]. For example, relative to placebo, 21 mg THC significantly increased SDLP by 3.5 cm, above the impairment threshold, in an on-road study [29]. Notably, significant THC-induced impairment on the SDLP was maintained throughout repeated testing at 40 min and 100 min after the start of smoking during actual on-road driving [36]. Importantly, several studies have directly compared driving simulator performance with real on-road driving, finding both oral THC and smoked THC significantly impaired driving performance, inclusive of SDLP, in simulated and real driving conditions [37, 38]. These studies suggest that driving simulators are valid and

sensitive in detecting cannabis-induced driving impairment. Given the logistical challenges associated with on-road controlled cannabis administration studies, simulated cannabis driving performance studies are essential for understanding how cannabis impairs driving ability [16]. The National Advanced Driving Simulator (NADS) is one of the most sophisticated simulators featuring highly realistic vehicle dynamics that enable studying driving performance based on complex and realistic scenarios. Using the NADS, vaporized cannabis with THC up to 6.7% increased SDLP similar to the impairments in lateral control induced by alcohol at common legal limits of 0.05% and 0.08% BAC [30]. Specifically, blood THC concentration of 8.2 µg/L THC observed post-vaporization was associated with ΔSDLP of 2.4 cm; blood THC concentration of 20 µg/L THC was associated with 5.2 cm ΔSDLP [30], which is considered "severe" [29]. Higher blood THC concentrations were also associated with greater impairment on a divided-attention task completed as part of the NADS simulation in the same study [39].

Biological Markers of Cannabis Impairment

At present, there are no reliable or practical biochemical or behavioral methods used in real-time with drivers on the road to determine cannabis-induced impairment. In contrast to the valid inferences about impairment from alcohol concentration levels, there is markedly poor correspondence between levels of THC in biological specimens (e.g., blood, saliva) and driving-related cognitive impairment [40]. Such poor correspondence produces significant challenges for cannabis-related driving policy and prevention efforts. Although blood THC concentrations generally correlate with magnitude of driving-related impairment, particularly at high THC blood concentrations, THC-induced impairment lasts long after the decline of THC in serum and oral fluid [15, 19]. Behavioral impairment is highest in the first hour after smoking with gradual decline over 4 h after use, when serum THC levels are no longer detectable [41]. Furthermore, substantial between-person variability exists in THC's pharmacokinetic profile, particularly immediately after smoking cannabis [22]. THC's metabolism is also affected by the ingestion mode with higher THC concentrations after vaporized cannabis followed by smoked cannabis and orally administered cannabis [42, 43]. Finally, significant associations between higher blood or oral fluid THC concentrations and greater performance impairment are observed among those using cannabis occasionally but not in individuals who use cannabis weekly or more frequently [40]. Thus, despite the reported associations between THC blood concentrations and car crash risk, there are no empirically-supported thresholds for blood or oral fluids that reliably indicate cannabis impairment [15].

Low Perceived Risk of DUIC

Despite substantial evidence of cannabis-impaired driving skill and crash risk, people who use cannabis generally endorse low perceived risk and impairment or even perceived safer driving after cannabis use [44]. More positive or permissive driving-related cognitions (i.e., peer norms, perceived dangerousness, and perceived negative consequences of DUIC) are predictive of greater likelihood of DUIC [2, 45, 46]. Positive DUIC cognitions (e.g., "DUIC is enjoyable") are strongly associated with DUIC intentions [47]. Many people who use cannabis equate slower driving with safer driving, which in turn lowers perceived risk and increases likelihood of DUIC [2]. Furthermore, higher cannabis intoxication levels perceived as safe for driving were associated with frequent past month DUIC [48].

Legal Standards for Cannabis-Impaired Driving in the U.S.

Currently globally and in the U.S. there are no universal impairment standards for DUIC. Even within the U.S., only about a third of the states have either zero-tolerance laws or per se driving laws for cannabis [49]. Zero tolerance laws define driving with any measurable amount of THC (and in some cases THC metabolites) as illegal. Per se laws set specific limits for THC with the lowest per se limit of 2 ng/mL of THC in the bloodstream in Nevada and the rest of the states in this category with a THC limit of 5 ng/mL. The majority of states do not have a specific legal limit and rely on detecting impairment in driver's performance (e.g., via field sobriety tests) for legal infraction. Therefore, the absence of consistent and scientifically backed legal standards necessitates a thorough understanding of controlled experimental research to adequately inform the evolving public policy landscape on cannabis-impaired driving.

The Current Review

The discrepancy between significant risks but permissive DUIC attitudes underscores the importance of disseminating accurate information to the public. In particular, it is important to translate the nuanced findings generated by controlled research with respect to the specific cannabinoid formulations and doses in relation to the duration of driving impairment that can be objectively detected. This type of translational approach is needed to help develop clear guidance on how long one should wait after consuming cannabis before one can drive safely. A comprehensive meta-analysis of 155 experimental trials concluded that waiting at least 5 h following inhaled cannabis and longer for oral THC formulations before driving is recommended [19]. The current

narrative review builds on this and other recent systematic reviews by summarizing evidence on the acute and residual effects of cannabis on driving performance from controlled research completed in the past five years [15, 19]. In addition to a few studies published in 2019 and 2020 included in the prior reviews, new trials published since 2020 were included in the present review. Controlled experimental research completed in recent years has expanded the published literature by extending the driving impairment assessment windows, expanding the modes of cannabis administration examined in prior studies (e.g., oromucosal), testing effects of cannabidiol (CBD) alone and combined with THC, and examining the joint influence of cannabis and alcohol on DUIC, given the high prevalence of co-use in traffic fatalities.

Methods

First, the authors conducted a literature search of articles published in the last 5 years from 2019 to 2024. The following key terms were searched using PubMed: [THC OR cannabis] AND driving AND [clinical study OR clinical trial OR randomized controlled trial]. Inclusion criteria were (1) a clinical trial or randomized controlled trial, (2) administered a cannabinoid and (3) experimentally assessed driving performance. Two authors (JM and NJB) reviewed articles independently and assessed whether they met the inclusion criteria.

Results

Search Criteria

The literature search resulted in a total of 66 articles. Forty-eight articles were removed after the abstract review because they did not meet the inclusion criteria. Studies were excluded due to observational rather than experimental designs, lack of cannabinoid administration, and/or non-driving related primary outcomes (i.e., craving or subjective response). After a full-text review, four additional articles were removed for not meeting inclusion criteria. The reason for rejection was that these study designs were not experimental. This resulted in 14 articles selected for review. Two additional articles that met the inclusion criteria for review were identified outside of the PubMed search through relevant citations within the selected articles [50, 51]. Thus, a total of 16 articles published between 2019 and 2024 were selected for inclusion. Table 1 presents sample characteristics and experimental design for the selected studies. Table 2 presents information on cannabinoid dose and mode of administration as well as driving assessments and outcomes in relation to cannabis administration.

Summary of Identified Studies

Of the 16 studies selected for inclusion, 13 utilized independent samples [39, 50–61]. Two [62, 63] were secondary data analyses of the Marcotte et al. (2022) clinical trial [57] and one [64] was a secondary data analysis of the Arkell et al. (2019) clinical trial [50]. The majority of the independent studies ($N = 12$) measured the effects of THC in minutes to hours after consumption. Suraev et al. (2024) deviated from this by assessing next day driving impairment 10 h after consumption [61]. In addition, Müller-Vahl et al. (2024) assessed driving performance after 9 weeks of stable treatment with an oromucosal THC/CBD spray [59]. The majority of study samples were comprised of individuals with regular recent use of cannabis [39, 52–55, 57]. Some studies enrolled individuals based on infrequent or lifetime cannabis use [50, 51, 56, 60] and some explicitly called for no recent use of cannabis as part of eligibility [58, 59, 61] (see Table 1 for additional details on sample characteristics).

THC's Effect on Driving Skills

A consensus emerged across the studies indicating that THC acutely impairs driving skills compared to placebo conditions. Specifically, most studies assessed SDLP and found that THC acutely increased SDLP relative to placebo. Significant differences in drug effect were found post-inhalation at 30 min (Fares at al 2022), at 30 and 90 min (Marcotte et al., 2022), at 30 and 210 min (Arkell et al., 2019), at 40–100 min (Arkell et al., 2020), and between 30 and 78 min (Miller et al. 2020) [39, 50, 51, 57, 57]. One study reported THC reduced SDLP, which in turn reduced driving confidence over the 8 h testing period post-inhalation; however, dose by time interaction effects on SDLP were not reported [55]. Brands et al. (2019) was an exception, as they did not find significant differences in SDLP between THC and placebo groups at 30 min post-smoking [52]. Orally ingested THC did not increase SDLP at 100–210 min [60]. Similarly, sublingual THC administration did not increase SDLP, relative to placebo, at 100 min [56]. Suraev et al. (2024) only tested for residual effects at 10 h and found no significant differences in sublingually administered THC relative to placebo on SDLP [61]. Other studies exclusively tested cannabidiol's effects on driving performance and did not include active THC conditions [53, 58]. Beyond SDLP, various other driving performance outcomes were examined, with differing findings across studies. Brands et al. (2019) observed that THC acutely reduced driving speed compared to placebo [52]. Similarly, Manning et al. (2023) reported an increased

Table 1 Summary of study sample characteristics and study designs

Author/year	Sample (*N*, type)	Sex (% male)	Age (M/SD)	Study Design
Arkell et al. 2019	*N* = 14; healthy adults with infrequent cannabis use (≤2 uses/week in the past 3 months and ≥10 lifetime exposures).	78.6	27.5 (4.5)	Within-subjects
Arkell et al. 2021 (secondary data analysis from Arkell et al., 2019)	*N* = 14; healthy adults with infrequent cannabis use (≤2 uses/week in the past 3 months and ≥10 lifetime exposures).	78.6	27.5 (4.5)	Within-subjects
Arkell et al. 2020	*N* = 26; healthy adults with a history of occasional cannabis use (<2x per week in the past 12 months and more than 10 lifetime exposures).	38.5	23.2 (2.6)	Within-subjects
Marcotte et al. 2022	*N* = 191; healthy adults with cannabis use≥4x in the past month.	61.8	29.9 (8.3)	Between-subjects
Fitzgerald et al. 2023 (secondary data analysis from Marcotte et al., 2022)	*N* = 191; healthy adults with cannabis use≥4x over past month.	61.8	29.9 (8.3)	Between-subjects
Hubbard et al. 2021 (secondary data analysis from Marcotte et al., 2022)	*N* = 191; healthy adults with cannabis use≥4x over past month. Participants were classified as "frequent or occasional users" based on self-reported cannabis use of ≥4/week or <4/week, respectively.	61.8	29.9 (8.3)	Between-subjects
Fares et al. 2022	*N* = 28; healthy young adults with at least 1x cannabis use per week and heavy drinking (5 + drinks for males; 4 + drinks for females).	57.1	22.5 (0.5)	Within-subjects
Egloff et al. 2023	*N* = 27; Healthy adults with experience of smoking cannabis or tobacco; consumption of cannabis-products once weekly or less.	59.2	28.9 (12.5)	Within-subjects
Brands et al. 2019	*N* = 91; Healthy young adults who regularly use cannabis (1–4 days per week).	71.6 (average across 3 groups)	22.1 (2.0) (average across 3 groups)	Between-subjects
Hartley et al. 2023	*N* = 30; Healthy male adults who consumed cannabis for at least the past 12 months, including occasional (1–2 joints per week; *n* = 15) and chronic (1–2 joints per day) consumers (*n* = 15).	100	Eligibility based on ages 20–34	Within-subjects
McCartney et al. 2022	*N* = 17; healthy adults without cannabis use in the past 3 months.	58.8	27.9 (7.0)	Within-subjects
Schnakenberg Martin et al. 2023	*N* = 18; healthy adults with lifetime exposure to cannabis.	61.1	30.2 (6.9)	Within-subjects
Manning et al. 2023	*N* = 31; healthy adults with prior cannabinoid product experience.	51.6	38.1 (10.8)	Within-subjects
Suraev et al. 2024	*N* = 20; healthy adults diagnosed with insomnia without cannabis use in the past 3 months.	20.0	46.1 (8.6)	Within-subjects
Müller-Vahl et al. 2024	*N* = 64; adults with a diagnosed tic disorder without cannabis use in the past 30 days.	77.6	36.8 (13.9)	Between-subjects
Miller et al., 2020	*N* = 19; healthy adults with cannabis use≥1-3x a month but ≤3 days/week in the past 3 months.	68.0	21–37 (age range)	Within-subjects

standard deviation of speed and oculomotor disturbances, such as increased fixation duration and decreased blink duration, in the THC group relative to placebo [56]. Fitzgerald et al. (2023) found that THC groups exhibited significantly worse performance on field sobriety tests, relative to placebo [62]. Furthermore, Hartley et al. (2023) noted that smoked THC increased reaction times [55]. Arkell et al. (2019) found that the combined THC/CBD dose increased standard deviation of headway (i.e., distance between the participant's vehicle and the vehicle ahead of it) relative to placebo at 210 min [50]. Conversely, several studies did not find significant THC-related differences in driving speed. Arkell et al. (2020), Fares et al. (2022), Schnakenberg Martin et al. (2023), and Suraev et al. (2024) all reported no significant differences in either mean driving speed or driving speed standard deviation compared to placebo [51, 54, 60, 61]. Similarly, Suraev et al. (2024) found no THC-related residual effects on headway or standard deviation of headway [61].

THC Dose Response on Driving Impairment

Studies examining THC dose-dependent changes on driving impairment have utilized a range of THC concentrations, from 1.8 mg to 125 mg in inhaled cannabis [39, 50–55, 57]. One study used an oral THC dose of 10 mg [60]. Sublingual doses ranged between 5 mg and 10 mg [56, 61] and one study used an oromucosal spray with an average dose of 18.4 mg THC [59]. About half of the studies used a fixed dose administered under standardized inhalation procedures

Table 2 Summary of study findings on cannabis's effects on driving performance

Author/year	Cannabinoid, dose, mode of administration, ad libitum/fixed dose	Driving performance outcome(s)	Time of assessment (# of mins relative to cannabis administration)	Primary SDLP Results	Secondary Driving Outcome Results
Arkell et al. 2019	**Dose**: • 11% THC (125 mg)/<1% CBD • 11% THC (125 mg)/11% CBD • Placebo (<1% THC, <1% CBD) **Mode**: Vaporized with standardized inhalation **Fixed Dose**	• SDLP • Mean headway • SD of headway	• 30 min • 210 min	• THC and THC/CBD increased SDLP at 30 and 210 min, relative to placebo.	• THC/CBD increased SD of headway at 210 min, relative to placebo
Arkell et al. 2021 (secondary data analysis from Arkell et al., 2019)	**Dose**: • 11% THC (125 mg)/<1% CBD • 11% THC (125 mg)/11% CBD • Placebo (<1% THC, <1% CBD) **Mode**: Vaporized with standardized inhalation **Fixed Dose**	• SDLP	• 30 min • 210 min	• THC increased SDLP (>2 cm change from placebo) in 50% of participants and THC/CBD in 57% at 30 min • THC increased SDLP in 43% of participants and THC/CBD in 71% of participants at 210 min	Plasma and oral fluid THC concentration did not correlate with SDLP
Arkell et al. 2020	**Dose**: • 22% (13.75 mg) THC/<1% CBD • <1% THC/9% CBD (13.75 mg) • 13.75 mg THC/CBD • Placebo **Mode**: Vaporized with standardized inhalation **Fixed Dose**	• SDLP • Mean Speed • SD of Speed	• 40 to 100 min • 240 min to 300 min	• THC and THC/CBD increased SDLP relative to placebo at 40 to 100 min • There were no significant differences at 240 to 300 min	• There were no significant differences in speed or SD of speed at any time point.
Marcotte et al. 2022	**Dose**: • 13.4% THC • 5.9% THC • Placebo **Mode**: Smoked cigarette **Ad libitum** over 10 min, minimum 4 puffs	Composite Drive Score (CDS) comprised of: • SDLP • SD of speed • Number of correct divided attention stimuli identified while driving	• 30 min • 90 min • 210 min • 270 min	• THC[1] significantly increased SDLP at 30 and 90 min compared to placebo • There were no differences in SDLP at 210–270 min compared to placebo	• The THC groups had significantly lower CDS scores at 30 and 90 min • There were no differences at 210–270 min, compared to placebo • CDS did not differ based on THC content
Fitzgerald et al. 2023 (secondary data analysis from Marcotte et al., 2022)	**Dose**: • 13.4% THC • 5.9% THC • Placebo **Mode**: Smoked cigarette **Ad libitum** over 10 min, minimum 4 puffs	• SDLP • Field sobriety tests	SDLP: • 26 min • 96 min • 211 min • 273 min Field Sobriety Tests: • 71 min • 139 min • 188 min • 252 min	• There was no correlation between blood, oral fluid, and breath THC levels with SDLP at any time point	• THC groups performed significantly worse on field sobriety tests at first, second, and third test timings

[50, 51, 53, 55]. The other half of the inhalation studies employed *ad libitum* cannabis administration, which makes it difficult to assess exactly how much THC was smoked or vaporized [39, 52, 57, 57]. Despite variations in THC concentrations used, only three studies directly compared several active THC doses and found a complex and indirect relationship between THC concentration and driving performance. Brands et al. (2019) categorized participants into low and high-THC groups based on a median split of measured blood THC concentrations but found no differences in

Table 2 (continued)

Author/year	Cannabinoid, dose, mode of administration, ad libitum/fixed dose	Driving performance outcome(s)	Time of assessment (# of mins relative to cannabis administration)	Primary SDLP Results	Secondary Driving Outcome Results
Hubbard et al. 2021 (secondary data analysis from Marcotte et al., 2022)	**Dose**: • 13.4% THC • 5.9% THC • Placebo **Mode**: Smoked cigarette **Ad libitum** over 10 min, minimum 4 puffs	Cannabinoid concentrations in: • Blood • Oral fluid (OF) • Breath	Biomarkers: • Pre-smoking • 30 min • 90 min • 180 min • 210 min • 240 min • 270 min • 271 + minutes	• SDLP was not tested as an independent outcome.	• Blood THC was not a useful marker of recent use (i.e., 3 h post-smoking). • Those who used frequently had more residual THC in blood and were more likely to be categorized as recently used prior to smoking; this was not the case with OF • OF at 10 ng/ml THC performed the best within 3 h post-smoking (92.5% PPV, 99.2% NPV) • Breath THC levels were detectable within the first 40 min post-smoking only
Fares et al. 2022	**Dose**: *Cannabis* • 12.5% (94 mg) THC • Placebo (< 0.1% THC) *Alcohol* • Target BrAC of 0.08% • Placebo **Mode**: Smoked cigarette **Cannabis**: **Ad libitum** for 10 min; 15 min following alcohol administration **Alcohol**: **Fixed** dose over 15 min	• SDLP • Mean of speed • SD of speed • Maximum speed • Reaction time (brake pedal latency)	• 30 min	• Alcohol-only, cannabis-only, and combined doses significantly increased SDLP relative to placebo	• Alcohol-only and combined doses significantly increased reaction time compared to placebo • No difference in mean speed, SD of speed
Egloff et al. 2023	**Dose**: • 0.64% (1.8 mg THC) and 14.6% (38 mg) CBD • 0.20% (0.6 mg) THC and 39 mg CBD • Placebo (< 0.2% cannabinoids) **Mode**: Vaporized with standardized procedure, 3 to 23 min in duration **Fixed Dose**	The following indices were derived from the DRIVESTA test for fitness to drive: • Logical reasoning • Concentration • Stress tolerance • Reaction time	• 1 h • 3 h	• SDLP was not tested as an independent outcome	• No significant differences in any metric
Brands et al. 2019	**Dose**: • 12.5% (93.75 mg) THC • Placebo (0.07 mg THC). **Mode**: Smoked cigarette **Ad libitum** for 10 min	• Mean speed • SDLP	• Baseline (prior to smoking) • 30 min • 24 h • 48 h	• THC did not increase SDLP at 30 min	• Mean speed significantly reduced by THC, relative to placebo, at 30 min
Hartley et al. 2023	**Dose**: • 10 mg THC • 30 mg THC • Placebo • **Mode**: smoked tobacco (1 gr) cigarette mixed with cannabis **Fixed Dose**	• SDLP • Reaction time • Self-reported driving confidence	• Baseline • 1 h • 2 h • 4 h • 6 h • 8 h, • 12 h • 24 h	• Driving confidence decreased at 1, 2, 4, 6 and 8 h • Higher SDLP was associated with lower driving confidence	• THC increased reaction time relative to placebo • Higher blood THC concentration was associated with slower reaction time

Table 2 (continued)

Author/year	Cannabinoid, dose, mode of administration, ad libitum/fixed dose	Driving performance outcome(s)	Time of assessment (# of mins relative to cannabis administration)	Primary SDLP Results	Secondary Driving Outcome Results
McCartney et al. 2022	**Dose**: • 1500 mg CBD • 300 mg CBD • 15 mg CBD • Placebo CBD **Mode**: Oral ingestion **Fixed Dose**	• SDLP • Headway • SD of headway • speed • SD of speed	• 45 to 75 min • 210 to 240 min	• There were no significant differences in SDLP relative to placebo.	• There were no significant differences in secondary driving performance metrics relative to placebo.
Schnakenberg Martin et al. 2023	**Dose**: *Cannabis* • 10 mg THC • Placebo *Alcohol* • intravenous alcohol (target 0.04 BAC) • Placebo infusion **Mode**: Oral ingestion (cannabis) 60 min prior to intravenous alcohol/placebo infusion **Fixed dose**	• SDLP • Mean speed • Number of speed exceedances • Self-reported ability to drive	• Baseline • 100 min • 210 min	• No significant differences in THC relative to placebo on SDLP at any time point. • Significant difference between THC combined with alcohol and placebo on SDLP at 210 min.	• Reductions in self-reported perceived ability to drive for 6 h • No differences in speed
Manning et al. 2023	**Dose**: • 5 mg THC/100 mg CBD • Placebo **Mode**: Sublingual **Fixed Dose**	• SDLP • SD of speed • SD of steering • Gaze tracking	• 100 min	• No significant difference on SDLP between THC/CBD and placebo.	• Increased SD of speed, fixation duration and decreased blink duration
Suraev et al. 2024	**Dose**: • 10 mg THC/200 mg CBD • Placebo **Mode**: Sublingual **Fixed Dose**	• SDLP • Headway • SD headway • Speed • SD speed	• 10 h	• No significant difference on SDLP between THC/CBD and placebo.	• There were no secondary outcome differences
Müller-Vahl et al. 2024	**Dose**: • 1 spray = 2.7 mg THC and 2.5 mg CBD; maximum dose of 12 sprays: 32.4 mg THC and 30 mg CBD; Average dose during maintenance phase: 18.4 mg THC and 17.1 mg CBD • Placebo **Mode**: Oromucosal spray **Flexible Dose ranging from 1 to 12 sprays/day**	The following indices were derived from the DRIVESTA test for fitness to drive: • Fitness to drive • Stress tolerance • Reaction time • Perceptual speed • Concentration	• After 9 weeks of stable treatment with spray	• SDLP was not tested as an independent outcome	• There was a significant difference in reaction time • No other outcomes were significant
Miller et al., 2020	**Dose**: *Cannabis* • 6.7% (33.5 mg) THC • 2.9% (14.5 mg) THC • Placebo *Alcohol* • Target BrAC of 0.065% • Placebo **Mode**: Inhalation (vaporized) **Cannabis**: **Ad Libitum** for 10 min following alcohol administration **Alcohol**: **Fixed Dose**	• SDLP • Divided attention tasks while driving • Mean speed • SD of speed	SDLP: • 30 min to 1.3 h Blood collected: • 10 min • 25 min • 84 min • 138 min	• No association between blood THC concentration and SDLP • BrAC predicted increased SDLP on one driving task	• Blood THC concentration was associated with increased odds of failing divided attention tasks while driving

CBD = cannabidiol, *IV* = intravenous, SD = standard deviation, *SDLP* = standard deviation of lateral position, *THC* = Δ⁹-tetrahydrocannabinol

[1]The two THC groups were combined for analysis due to non-significant differences between the groups.

driving metrics between these THC groups [52]. Similarly, Marcotte et al. (2022) observed no significant differences in driving performance between 13.4% THC and 5.9% THC doses smoked *ad libitum* [57]. In contrast, Hartley et al. (2023) identified a dose-dependent effect such that the higher THC dose (30 mg) was associated with a lower self-reported driving confidence, which in turn was associated with a higher SDLP [55].

Furthermore, three studies estimated effects of THC on driving performance based on THC blood concentration levels rather than by study condition. Fitzgerald et al. (2023) collected blood, saliva, and breath samples 13 min after smoking and found no association between THC concentrations and SDLP at any time point [62]. Similarly, Miller at al. (2020) collected blood at 10-, 25-, 84- and 138-minutes post-inhalation [39]. They found that blood THC concentration was not associated with SDLP, although it was associated with decreased performance on the divided-attention tasks. Arkell et al. (2021) found no association between blood or oral THC concentration and SDLP at 30–210 min [64].

The Role of Cannabidiol (CBD)

Of the 16 identified studies, seven included a CBD condition: Arkell et al. (2019), Arkell et al. (2020), Manning et al. (2023), Egloff et al. (2023), McCartney et al. (2023), Suraev et al. (2024), and Müller-Vahl et al. (2024) [50, 51, 53, 56, 59, 61]. Only two of these studies compared driving outcomes under the effects of THC relative to CBD alone or to THC-CBD equivalent dose [50, 51]. Four studies tested combined effects of CBD and THC relative to placebo (Manning et al., 2023; Egloff et al., 2023; Suraev et al., 2024; and Müller-Vahl et al., 2024), and one study exclusively examined driving performance with CBD-only dosing (McCartney et al., 2022) [53, 56, 58, 59, 61]. McCartney's et al. (2022) study on simulated driving with CBD found that oral CBD did not increase SDLP, impair cognitive functions, or induce subjective feelings of intoxication [58]. It noted CBD's persistence in plasma over extended periods. Arkell et al. (2019) tested a THC-dominant and a THC-CBD equivalent dose in inhaled cannabis and found both of the active doses significantly increased SDLP, relative to placebo, but did not differ from each other [50]. Arkell et al. (2020) examined a CBD-dominant inhaled dose and did not find a statistically significant increase in SDLP relative to placebo [51]. Manning et al. (2023) compared a 5 mg THC/100 mg CBD sublingual dose relative to placebo and did not find significant differences in SDLP [56]. They suggested that a high CBD-to-THC ratio may have mitigated some THC-induced driving impairments. Meanwhile, Egloff et al. (2023) compared very low THC doses mixed with CBD (1.8 mg THC/38 mg CBD and 0.6 mg/39 mg CBD) and did not find any significant differences in fitness to drive tests between these inhaled CBD-dominant doses relative to placebo [53]. Lastly, Suraev et al., examined the next-day driving performance (i.e., 10 h after sublingual 10 mg THC/200 mg CBD administration) and did not find any significant differences in SDLP relative to placebo [61]. In summary, a consensus across studies suggests that CBD alone is not associated with driving impairment.

Effects of Combined Cannabis and Alcohol Use

The selected studies demonstrated that the combined use of cannabis and alcohol resulted in a greater impairment of driving-related skills compared to the use of either substance alone. Fares et al. (2022) utilized a within-subjects, two-group design with both alcohol (target dose of 0.08% breath alcohol concentration [BrAC] vs. placebo) and cannabis (12.5% THC vs. placebo) administrations [54]. Their results indicated an additive effect on SDLP, with both alcohol and cannabis independently increasing SDLP. Critically, the combined use of alcohol and THC resulted in significantly greater SDLP than either substance used individually, demonstrating the amplified impairment from co-use. Schnakenberg Martin et al. (2023) similarly demonstrated an additive effect using a crossover design. Their study involved intravenous ethanol (target BAC of 0.04% vs. saline placebo) and oral THC (10 mg THC vs. placebo) administration [60]. Consistent with Fares et al. (2022), they found that combined administration led to greater SDLP compared to the effects of ethanol or THC in isolation, further reinforcing the additive nature of the combined impairment [54]. Miller et al. (2020) employed a within-subjects design with alcohol (target dose of 0.065% BrAC vs. placebo) and cannabis (6.7% THC, 2.9% THC, placebo) administrations and found evidence of independent impairment [39]. While they observed that both BrAC and blood THC levels were independently predictive of driving skill deficits, importantly, their findings indicated no significant interaction effects suggesting THC and alcohol have additive, but not synergistic, effects.

Subjective Perception of Impairment

Many of the identified studies demonstrated a relationship between subjective feelings of impairment and actual driving performance following cannabis consumption. Brands et al. (2019) initially highlighted this by observing that over 25% of participants, even shortly after smoking cannabis and undergoing a driving simulation, expressed willingness to drive a real vehicle, although the timing of willingness since inhalation was not clear [52]. Marcotte et al. (2022) found that while participants reported feeling impaired

immediately after smoking cannabis, their self-assessed readiness to drive increased over time, even though simulated driving performance did not show corresponding improvement [57]. Although participants acknowledged cannabis's greater impact on their performance compared to placebo across all time points, their self-evaluation of driving ability was significantly worse than placebo only at the 30-minute mark, suggesting a limited correlation between perceived and actual impairment over time. Arkell et al. (2020)'s findings align with this, indicating that driving confidence only partially tracked objective measures of driving ability, like SDLP. However, their study also revealed that post-hoc evaluations of driving ability, assessed 40–100 min after inhalation, were more accurate, suggesting that participants were better at judging their driving performance after the fact than predicting it in the moment [51].

Biomarkers of Cannabis Use

Several studies highlight the variability and rapid decline of THC in blood, complicating its use as a reliable impairment indicator. Brands et al. (2019)'s research demonstrated considerable variability in blood THC levels among participants [52]. This variability is consistent with that found by Hubbard et al. (2021), who noted that peak blood THC concentrations decrease dramatically by as much as 90% within 1.5 h [63]. They also noted that more frequent THC use was associated with higher levels of residual blood THC values at baseline, making it difficult to compare between participants. Consistent with these observations, many studies have found weak or non-existent correlations between THC concentrations in blood, oral fluid (OF), or breath and actual driving performance or impairment [56, 57, 62]. Nonetheless, Fitzgerald et al. (2023) found that OF values combined with field sobriety tests can significantly improve impairment classification results compared to using either approach alone [62]. These findings collectively underscore that THC concentrations in common biofluids (e.g., blood and saliva) and exhaled breath are unreliable as sole indicators of current driving impairment. Cannabinol (CBN) blood concentration had some promise as a biomarker for recent use (within 3 h) [63]. However, while CBN exhibited high specificity, its sensitivity at a low threshold was relatively low and further limitations to this approach may be due to its variable presence across cannabis chemovars.

Discussion

As cannabis use has become more prevalent and DUIC more wide-spread, there are increasing concerns over road safety and motor-vehicle accidents involving cannabis-impaired drivers. The impact of cannabis on driving impairment has been examined widely across epidemiological and experimental studies, although the recent expansion of the cannabis legal market, along with the many new formulations, calls for more research to fully understand its effects on driving impairment. This review focused on recent studies providing the most compelling evidence examining cannabis-related driving impairment based on placebo-controlled research with an emphasis on the cannabinoid composition, mode of administration, timing of driving performance, and standardized indices of driving performance. While studies varied in terms of the cannabinoids, dosing, and modes of administration, the majority used SDLP as the universal standard of driving impairment. This allowed for comparisons across studies published in the past five years included in this review as well as the prior literature that provides information on driving impairment from alcohol and drugs other than cannabis. There was strong consensus across studies on acute impairment induced by inhaled cannabis on SDLP, exceeding the criterion of 2.4 cm change indicative of detectable driving problems. Oral and oromucosal/sublingual THC administration did not acutely change SDLP. Below we discuss implications of these recent findings in the context of prior research and offer recommendations for the next steps in the field of DUIC research as well as DUIC prevention and policy.

While dose-dependent effects of THC on driving-related cognitive and psychomotor impairment are well-established [18], only four studies included in this review utilized more than one dose of inhaled THC and none found differences between active THC doses on SDLP, the primary outcome of interest [39, 50, 55, 57]. Seven studies examined acute effects of smoked or vaporized THC, ranging from 2.9% THC to 22%, on driving outcomes [39, 50–52, 54, 55, 57]. However, there was insufficient information from these studies to determine the actual dose of THC inhaled, as most trials employed *ad libitum* administration and did not report the total plant material smoked or vaporized. There is evidence that individuals titrate THC doses when using higher potency products such that equivalent intoxication levels are reached [65, 66]. However, there are mixed findings on whether reductions in quantity are proportional to THC content, and higher THC blood levels along with more pronounced acute effects are still observed [67]. Given that all studies ranging in THC doses found cannabis significantly impaired driving, it is evident that inhaled THC even in the low dose range increases DUIC risk. Given only a few studies utilized oral, oromucosal inclusive of sublingual THC administration [56, 59–61], conclusions about these alternative routes of administration should be tempered.

The information on the effects on cannabidiol (CBD), the nonpsychoactive cannabinoid in the cannabis sativa plant,

on driving outcomes in this review addresses an important knowledge gap in prior published reviews of cannabis driving impairment. The effect of CBD on driving impairment was examined in six studies [50, 51, 53, 56, 58, 61] and an additional study examined the long-term impact of CBD on driving outcomes after a 9-week treatment [59]. The three studies that administered CBD alone or with very low (< 1%) THC doses [51, 53, 58] found no impairment on SDLP or driving-related ability. The other studies that examined combined THC/CBD doses also did not find acute or residual effects of CBD on SDLP [50, 56, 59, 61]. Cannabidiol is one of the few FDA-approved cannabinoid-based pharmacotherapies (for treatment of seizures in certain forms of epilepsy) and is widely used by the general public for a number of medical and mental health conditions [50]. Thus, we expect many people to drive after using CBD either alone or in combination with THC in their cannabis products. While CBD is not associated with cognitive impairment [68], it has been found to increase somnolence and sedation at high doses [69, 70]. However, a recent meta-analysis concluded that these adverse effects of CBD are limited to childhood epilepsy studies and that subclinical doses of CBD (< 300 mg) are typically used outside of clinical trials [71]. With the exception of the McCartney et al. (2022) study [58], our review included studies in which relatively low CBD doses were administered. Lack of impairment in driving performance from CBD highlighted in this review is consistent with the broader literature.

Studies that examined combined effects of cannabis and alcohol on driving performance found additive effects of each substance on SDLP [39, 54, 60]. This suggests that using both substances simultaneously leads to greater deficits in driving skill than using either substance alone. These findings are consistent with prior research and with pharmacokinetic studies that find that even at low doses, the combination of alcohol and THC results in higher THC blood levels, which can amplify impairment [30, 72, 73].

Perhaps one of the most critical questions of public interest is how long driving impairment can be detected after cannabis use. The findings summarized in this review suggest that driving impairment was consistently observed within the first hour after inhalation in most studies, and was still detected at 3.5 h post-inhalation [50] with most driving-related skills returning to normal within 5 h [51, 57]. The one study that utilized oral THC (10 mg) administration did not find significant effects on SDLP at 100–210 min [60]. Two studies with sublingual THC administration did not find significant effects on SDLP at 100 min (5 mg; Manning et al., 2023) or at 10 h (10 mg; Suraev et al., 2024) [56, 61]; although, several other indices of driving performance were acutely affected by sublingual THC dose [56]. Several studies extended assessment windows outside of the acute effect range to examine residual effects of cannabis on driving. For example, Hartley et al. (2023) [55] repeated driving tests at 12 h and 24 h post-smoking, Brands et al. (2019) [52] at 24 h and 48 h post-smoking, Suraev et al. (2024) [61] at 10 h post-sublingual administration, and one study assessed effects of a 9-week treatment with oromucosal spray, nabiximols, on driving impairment [59]. Although several studies in this review specifically examined the effects of oral or sublingually-ingested cannabinoids on driving, these studies used relatively low doses of THC (up to 10 mg). With the rapidly expanding cannabis edible industry [74], more research is needed with oral and sublingual THC preparations of higher doses as well as the emerging "fast-acting" edible formulation [75].

To translate these and prior research findings into clear public health messaging, waiting for at least 5 h following smoking or vaporizing cannabis should reduce the risk of impaired driving; waiting longer after orally-ingested cannabis products may be necessary to avoid driving under the influence. Our recommendation based on controlled research completed in the past five years is consistent with that of a much larger recent systematic and meta-analytic review that concluded that most driving-related cognitive skills would recover within ~ 5 h (and almost all within ~ 7 h) of inhaling 20 mg THC [19]. Avoiding driving while using cannabis or immediately after is absolutely imperative to reduce crash risk. In epidemiological studies, driving within one hour of smoking cannabis was associated with higher motor-vehicle accidents than driving within 2 h or longer [24]. In line with larger syntheses [19], we are unable to offer specific recommendations for modes of administration other than inhalation due to very few studies testing oral or oromucosal THC administrations. Notably, these general guidelines do not take into account variations in driving performance due to individual experience with cannabis, inhalation topography, and interaction with other substances or medications taken at the time of driving [24].

Public health campaigns geared at DUIC prevention are currently focused on messaging that relies on perceived feeling of intoxication. For example, "If you feel different, you drive different. Drive high, get a DUI" [76]. Experimental studies suggest that drivers exhibit some awareness that cannabis impairs driving ability, as they compensate by slowing down [35]. However, this compensation may actually contribute to increased likelihood of DUIC. Such efforts are largely unsuccessful because of the large variety of driving-related skills that are affected by THC (e.g., cognitive performance and judgment)--and yet may create a false perception of safer driving. The findings in the current review corroborate this notion, as participants endorsed willingness or readiness to drive shortly after using cannabis when their driving performance was objectively impaired [51, 52, 57]. This is consistent with prior literature that highlighted individual willingness to drive for an important reason or when individuals believed they have tolerance to cannabis's effects

[24]. Thus, having more clear guidelines tailored by cannabis formulation on how long to wait before driving is more prudent than relying on self-assessed subjective intoxication.

Conclusions

Controlled studies in this review align with prior research demonstrating inhaled cannabis with THC acutely impairs driving. However, there is limited evidence regarding the effects of oral and sublingual THC administration. The impact of CBD, the non-psychoactive cannabinoid, on driving performance is negligible at doses typically used outside clinical settings. When combined with alcohol, cannabis amplifies driving impairment, highlighting the increased risk of DUIC when both substances are used together. Linking recent cannabis use to driving impairment outside of the laboratory is challenging due to poor correspondence between THC levels in biological markers (such as blood or oral fluids) and behavioral measures of impairment. Experimental research points to deficiencies in the per se approach to DUIC [64]. Advances in technology could enhance the precision and accuracy of establishing cannabis impairment. A "successful hurdles" approach that relies on a highly sensitive biomarker to detect recent cannabis use followed by behavioral assessment of impairment that has high specificity has been recommended [8]. More research is needed to develop a consistent impairment standard for DUIC. Development of technology would not only expand the law enforcement's capacity to evaluate drivers for DUIC but could also aid individuals in making safer decisions to avoid impaired driving. For now, public health campaigns should emphasize clear guidelines on how long to wait after cannabis use before driving, rather than relying on self-assessed intoxication, to help reduce the risk of DUIC. Ultimately, clear and enforceable DUIC policies can impact permissive attitudes towards DUIC.

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    - A systematic review and meta-analysis of studies that measured either car driving performance or cognitive skill related to car driving following acute THC administration in a placebo-controlled experimental trial. 155 trials derived from 80 original research studies were included in the systematic review and 106 trials were included in quantitative synthesis.
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    - A meta-analysis of studies that measured either car driving performance or cognitive skill related to car driving following acute THC administration via inhalation or oral ingestion and a THC biomarker in a placebo-controlled experimental trial. 28 original research studies with 822 driving-related outcomes and biomarkers were included in the meta-analysis.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

Human and Animal Rights and Informed Consent (No animal or human subjects by the authors were used in this review).

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